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CRYSTAL STRUCTURE OF  $\epsilon$ -PLA<sub>2</sub> AND METHODS OF IDENTIFYING  
5 AGONSITS AND ANTAGONISTS USING SAME

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SPECIFICAION

## CRYSTAL STRUCTURE OF CPLA<sub>2</sub> AND METHODS OF IDENTIFYING AGONISTS AND ANTAGONISTS USING SAME

5        The material contained on the Compact Disc-Recordable (CD-R) in  
the following file: "Table 2.txt" is hereby incorporated by reference in its  
entirety. The file named "Table 2.txt" contains Table 2, which contains the  
structural coordinates of cytosolic phospholipase A<sub>2</sub> (cPLA<sub>2</sub>). The file  
named "Table 2.txt" was created on March 22, 2002 and is 854KB. The CD-  
10 R was formatted from an IBM-PC and is compatible with MS-Windows,  
and is submitted in duplicate. Both CD-Rs, Copy 1 and Copy 2, are labeled  
with the name of the inventors, the title of the invention, the attorney  
docket number ("GFN-5341"), the creation date ("March 22, 2002"), "Table  
2", and "Copy 1" or "Copy 2." The file contained on the CD-R is  
15 understood to comply with the requirements of 37 C.F.R. §1.52 and 37  
C.F.R. §1.58.

### Background of the Invention

Leukotrienes and prostaglandins are inflammatory mediators  
20 important in asthma, arthritis, and other inflammatory diseases.  
Leukotrienes cause airway obstruction in asthmatics through  
bronchoconstriction, increased mucus secretion, and chemoattraction of  
inflammatory cells (O'Byrne, 1997); prostaglandins cause pain and edema  
associated with arthritis. Pharmacological intervention blocking either the  
25 synthesis or action of these lipid mediators is effective in treating human  
disease, thus confirming their importance (Simon et al., 1998; O'Byrne,  
1997).

Cytosolic phospholipase A<sub>2</sub> (cPLA<sub>2</sub>) initiates the production of  
30 leukotrienes and prostaglandins by releasing arachidonic acid from cellular  
membranes. Arachidonic acid in turn is metabolized to prostaglandins by

the cyclooxygenase pathway and to leukotrienes by the 5-lipoxygenase pathway. Concomitant with the release of arachidonic acid, lyso-platelet-activating factor (lyso-PAF) is formed, which can then be acetylated to generate PAF, a molecule also implicated in the pathophysiology of asthma and arthritis (Venable et al., 1993). Hence, the reaction catalyzed by cPLA<sub>2</sub> initiates the production of three classes of inflammatory mediators: leukotrienes, prostaglandins, and PAF.

cPLA<sub>2</sub> is a member of a diverse superfamily of phospholipase A<sub>2</sub> enzymes with the common ability to cleave the *sn*-2 ester of glycerophospholipids. The first members of the family to be characterized were the low molecular weight enzymes that are secreted either extracellularly or into granules (and are here collectively referred to as sPLA<sub>2</sub>s; groups I, II, III, V, VII, and IX) (Dennis, 1997). The PLA<sub>2</sub> family has expanded with the cloning and characterization of calcium-dependent arachidonyl-selective cPLA<sub>2</sub> (Clark et al., 1991; Kramer et al., 1991), the calcium-independent PLA<sub>2</sub> (Tang et al., 1997; Balboa et al., 1997) and the plasma and intracellular PAF-acetylhydrolases (Hattori et al., 1994, 1995). Each of these new enzymes shares no sequence homology with the low molecular weight enzymes or with each other. In addition, unlike sPLA<sub>2</sub>s, which use activated water to cleave the phospholipid, these enzymes appear to use a nucleophilic serine. In this respect, they have more in common with other lipases of the  $\alpha/\beta$  hydrolase family than with the sPLA<sub>2</sub>s. Two additional enzymes with 30% identity to the catalytic domain of cPLA<sub>2</sub> have recently been cloned; they have been termed cPLA<sub>2</sub> $\beta$  (C. Song et al., manuscript in preparation) and cPLA<sub>2</sub> $\gamma$  (Underwood et al., 1998).

The cloning of cPLA<sub>2</sub> is also described in U.S. Patent Nos. 5,322,776, 5,354,677, 5,527,698 and 5,593,878. The cloning of calcium-independent

cPLA<sub>2</sub> is also described in U.S. Patent Nos. 5,466,595, 5,554,511, 5,589,170 and 5,840,511.

Numerous pieces of evidence have supported the central role of cPLA<sub>2</sub> in lipid mediator biosynthesis. cPLA<sub>2</sub> is the only enzyme which is highly selective for phospholipids containing arachidonic acid in the *sn*-2 position (Clark et al., 1995; Hanel & Gelb, 1993). Activation of cPLA<sub>2</sub> or its increased expression have been linked with increased leukotriene and prostaglandin synthesis (Lin et al., 1992b). Following activation, cPLA<sub>2</sub> translocates to the nuclear membrane, where it is co-localized with the cyclooxygenase and lipoxygenase that metabolize arachidonate to prostaglandins and leukotrienes (Schievella et al., Glover et al., 1995). Although these data are compelling, the most definitive evidence for the central role of cPLA<sub>2</sub> in eicosanoid and PAF production came from mice made deficient in cPLA<sub>2</sub> through homologous recombination (Uozumi et al., 1997; Bonventre et al., 1997). Peritoneal macrophages derived from these animals failed to make leukotrienes, prostaglandins, or PAF. The cPLA<sub>2</sub> deficient mice have also been informative of the role of cPLA<sub>2</sub> in disease, since these mice are resistant to bronchial hyperreactivity in an anaphylaxis model used to mimic asthma (Uozumi et al., 1997).

cPLA<sub>2</sub> consists of at least two functionally distinct domains: a N-terminal Ca<sup>2+</sup>-dependent lipid-binding (CaLB) domain and a Ca<sup>2+</sup>-independent catalytic domain (Nalefski et al., 1994). The N-terminal CaLB domain is a member of the C2 family and its structure has been solved (Perisic et al., 1998; Xu et al., 1998); it mediates calcium regulation by co-localizing the catalytic domain with its membrane substrate (Nalefski et al., 1994). cPLA<sub>2</sub> activity, in addition, is also regulated by phosphorylation of the catalytic domain (Lin et al., 1991; Leslie, 1997). Ser505 (of SEQ ID NO:2) and Ser727 (of SEQ ID NO:2) are conserved across all species and are

phosphorylated in multiple cell types (de Carvalho et al., 1998).  
Phosphorylation of Ser505 (of SEQ ID NO:2) by members of the MAP-kinase family is a common response to extracellular stimuli that release arachidonic acid. Mutation of Ser505 (of SEQ ID NO:2) to Ala decreases  
5 activation (Lin et al., 1993) whereas the analogous mutation on Ser727 (of SEQ ID NO:2) has no effect (Leslie, 1998).

Several lines of evidence suggest that the catalytic mechanism of cPLA<sub>2</sub> proceeds through a serine-acyl intermediate (Trimble et al., 1993;  
10 Hanel & Gelb, 1995). Mutation of Ser228 (of SEQ ID NO:2) abolishes cPLA<sub>2</sub> activity against all substrates including phospholipids, lysophospholipids, and fatty acylated coumarin (Pickard et al., 1996; Huang et al., 1996). Ser228 (of SEQ ID NO:2) is present in a pentapeptide sequence, G-L-S-G-S (SEQ ID NO:3), which is similar to the classic "lipase motif" G-X-S-X-G  
15 (Schrage & Cygler, 1997) found in most lipases within the broader family of enzymes called the  $\alpha/\beta$  hydrolases. These enzymes possess a common core which consists of a well-conserved mixed  $\beta$  sheet whose strands are interspersed by  $\alpha$  helices. In all  $\alpha/\beta$  hydrolases, the catalytic serine is present in a tight turn between a  $\beta$ -strand and an  $\alpha$ -helix, termed the  
20 "nucleophilic elbow" (see review by Schrage & Cygler, 1997). This turn directs the short serine side chain away from the protein backbone, reducing the steric hindrance about the residue and requiring that the +2 and -2 sidechains be small to avoid steric clash; thus the prevalence of the G-X-S-X-G motif (Derewenda & Derewenda, 1991).

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In addition to serine,  $\alpha/\beta$  hydrolases use a histidine and an acid (aspartate/ glutamate) as the other members of a catalytic triad similar to that present in serine proteases (Schrage & Cygler, 1997). However, although in cPLA<sub>2</sub> Asp549 (of SEQ ID NO:2) was shown to be essential for  
30 activity, none of the 19 histidine residues were (Pickard et al., 1996). A

different residue, Arg200 (of SEQ ID NO:2), was implicated as playing a role in the enzymatic process, although the mechanism for its involvement remained unknown. These observations suggested that cPLA<sub>2</sub> acts through a novel catalytic mechanism for acyl hydrolases.

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Like both the sPLA<sub>2</sub>s and the lipases of the  $\alpha/\beta$  hydrolase family, cPLA<sub>2</sub> preferentially cleaves substrates presented in an interface (Nalefski et al., 1994). This phenomenon, known as interfacial activation, has been attributed to either conformational changes in the enzyme or more  
10 favorable presentation of the substrate (Scott et al., 1990). The origin of the 1500-fold difference in cPLA<sub>2</sub> activity toward monomeric and micellar substrate remains unknown.

Despite the key role of cPLA<sub>2</sub> in inflammatory disease, its three-  
15 dimensional structure remained unsolved, leaving numerous questions unanswered. Here we report the x-ray crystal structure of human cPLA<sub>2</sub> at 2.5 Å resolution. The structure provides insight into the origin of arachidonate selectivity and interfacial activation, clarifies the roles of Ser228, Asp549, and Arg200 (of SEQ ID NO:2), and reveals the interplay  
20 between CaLB and the catalytic domains. Importantly, the structure is of a unique topology, distinct from that of the  $\alpha/\beta$  hydrolase family.

## Summary of the Invention

All references to amino acids in cPLA2 herein are made using residue numbers which refer to the cPLA2 sequence found in SEQ ID NO:2 and in Table I of U.S. Patent No. 5,527,698, with the first methionine being  
5 designated residue 1 (Met1).

The present invention provides for crystalline cPLA2. Preferably, the cPLA2 is either human cPLA2 or cPLA2 from a non-mammalian species. In certain embodiments, the cPLA2 is recombinant cPLA2 and/or comprises the mature sequence of naturally-occurring cPLA2.

10 Other embodiments provide for a crystalline composition comprising cPLA2 is-in association with a second chemical species. Preferably, the second chemical species is selected from the group consisting of a potential inhibitor of cPLA2 activity and a potential inhibitor of cPLA2 membrane binding.

15 Yet other embodiments provide for a model of the structure of cPLA2 comprising a data set embodying the structure of cPLA2. Preferably, such data set was determined by crystallographic analysis of cPLA2, including possibly by NMR analysis. In certain embodiments, the data set embodies a portion of the structure of cPLA2, including without  
20 limitation the active site of cPLA2 or the CaLB domain of cPLA2.

Any available method may be used to construct such model from the crystallographic and/or NMR data disclosed herein or obtained from independent analysis of crystalline cPLA2. Such a model can be constructed from available analytical data points using known software  
25 packages such as HKL, MOSFILM, XDS, CCP4, SHARP, PHASES, HEAVY, XPLOR, TNT, NMRCOMPASS, NMRPIPE, DIANA, NMRDRAW, FELIX, VNMR, MADIGRAS, QUANTA, BUSTER, SOLVE, O, FRODO, RASMOL, and CHAIN. The model constructed from these data can then be visualized using available systems, including, for example, Silicon  
30 Graphics, Evans and Sutherland, SUN, Hewlett Packard, Apple Macintosh,

DEC, IBM, and Compaq. The present invention also provides for a computer system which comprises the model of the invention and hardware used for construction, processing and/or visualization of the model of the invention.

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Further embodiments provide a computer system comprising computer hardware and the model of the present invention.

Methods are also provided for identifying a species which is an agonist or antagonist of cPLA2 activity or binding comprising: (a) providing the model of the present invention, (b) studying the interaction of candidate species with such model, and (c) selecting a species which is predicted to act as said agonist or antagonist. Species identified in accordance with such methods are also provided.

Other embodiments provide: (1) a process of identifying a substance that inhibits cPLA2 activity or binding comprising determining the interaction between a candidate substance and a model of the structure of cPLA2, or (2) a process of identifying a substance that mimics cPLA2 activity or binding comprising determining the interaction between a candidate substance and a model of the structure of cPLA2. Substances identified in accordance with such processes are also provided.

The study of the interaction of the candidate species with the model can be performed using available software platforms, including QUANTA, RASMOL, O, CHAIN, FRODO, INSIGHT, DOCK, MCSS/HOOK, CHARMM, LEAPFROG, CAVEAT(UC Berkley), CAVEAT(MSI), MODELLER, CATALYST, and ISIS.

Other embodiments provide a method of identifying inhibitors of cPLA2 activity by rational drug design comprising: (a) designing a potential inhibitor that will form non-covalent bonds with one or more amino acids in the cPLA2 active site based upon the crystal structure coordinates of cPLA2; (b) synthesizing the inhibitor; and (c) determining



whether the potential inhibitor inhibits the activity of cPLA2. Preferably, the crystal structure co-ordinates of cPLA2 used in such methods are obtained from a cPLA2 crystal of space group P2<sub>1</sub>2<sub>1</sub>2 with a = 153.59 angstroms, b = 95.49 angstroms, and c = 139.13 angstroms. In other

5 preferred embodiments, the inhibitor is designed to interact with one or more atoms of said one or more amino acids in the cPLA2 active site is selected from the group consisting of:

CB and O<sub>γ</sub> atoms of Ser228 of SEQ ID NO:2;

O<sub>δ1</sub> and O<sub>δ2</sub> atoms of Asp549 and Asp575 of SEQ ID NO:2;

10       CB, CG, CD, NE, CZ, NH1 and NH2 atoms of Arg200, Arg413 and Arg579 of SEQ ID NO:2;

Backbone carbonyl oxygen of Trp393 of SEQ ID NO:2;

N<sub>δ2</sub> and O<sub>δ1</sub> atoms of Asn555 of SEQ ID NO:2;

Atoms CD1, CE1, CG, CZ, CE2, and CD2 of Phe397, Phe681,

15       Phe683 and Phe199 of SEQ ID NO:2;

CG, CD1, NE1, CE2, CZ2, CH2, CZ3, CE3 and CD2 of Trp232 and Trp393 of SEQ ID NO:2;

CB and O<sub>γ</sub> atoms of Ser577 of SEQ ID NO:2;

Atom s CB and S<sub>γ</sub> of Cys331 of SEQ ID NO:2;

20       Atoms OE1 and OE2 of Glu589 of SEQ ID NO:2;

Atoms CB, CG, CD, CE and NZ of Lys588 of SEQ ID NO:2;

O<sub>γ1</sub> atom of Thr680 of SEQ ID NO:2;

OE1 and OE2 atoms of Glu418 and Glu422 of SEQ ID NO:2;

Atoms CB, CG, SD and CE of Met417 of SEQ ID NO:2;

25       Atoms CB, CG, CD1 and CD2 of Leu400 and Leu421 of SEQ ID NO:2;

Atoms CB, CG1, CG2, or CD1 of Ile424 of SEQ ID NO:2;

Backbone NH and carbonyl oxygen atoms of Ala578 of SEQ ID NO:2; and

Atoms CB, CG, ND1, CE1, NE2, and CD2 of His639 of SEQ ID

NO:2.

Agonists and antagonists identified by such methods are also provided.

Methods are also provided for identifying inhibitors of cPLA2

- 5 membrane binding by rational drug design comprising: (a) designing a potential inhibitor that will form non-covalent bonds with one or more amino acids in the cPLA2 electrostatic patch region based upon the crystal structure co-ordinates of cPLA2; (b) synthesizing the inhibitor; and (c) determining whether the potential inhibitor inhibits the membrane binding
- 10 of cPLA2. Preferably, the crystal structure co-ordinates of cPLA2 used in such methods are obtained from a cPLA2 crystal of space group P2<sub>1</sub>2<sub>1</sub>2 with a = 153.59 angstroms, b = 95.49 angstroms, and c = 139.13 angstroms. In other preferred embodiments, the inhibitor is designed to interact with one or more amino acids selected from the group consisting of Arg467,
- 15 Arg485, Lys488, Lys544 and Lys543 (all of SEQ ID NO:2). Agonists and antagonists identified by such methods are also provided.

### Brief Description of the Drawings

Fig. 1. Experimental map generated with MAD phases obtained from scattering of a single Tb atom per 749 residues of cPLA<sub>2</sub> (SEQ ID NO:2). Solvent flattening (60% solvent content) and 2-fold non-crystallographic symmetry averaging in DM were employed for map generation.

Fig. 2 (A). Ribbon diagram of the cPLA<sub>2</sub> monomer. The CaLB domain is shown in green, with the two Ca<sup>2+</sup> atoms depicted in red. The “cap” structure of cPLA<sub>2</sub> is colored purple. Mobile loops with poor electron density are shown as dots. The flexible linker between CaLB and the catalytic domain is colored red. The positions of the 4 serine residues which are phosphorylated in cPLA<sub>2</sub> are also shown. Figure prepared with Molscript (Kraulis, 1991) and RASTER3D (Bacon & Anderson, 1988).  
(B) GRASP surface diagram of cPLA<sub>2</sub>. Residues which presented N<sup>15</sup>/NH shifts upon interaction with dodecylphosphocholine micelles in NMR experiments by Xu et al. (1998) are colored purple. The cPLA<sub>2</sub> active cleft is highlighted in red. Lid residues have been removed for clarity.  
(C) Surface potential representation of cPLA<sub>2</sub>, with basic residues in blue shades and acidic residues in red. The lid residues have been removed for clarity. A highly basic patch is clearly visible on the membrane-binding region of the molecule. Figure prepared with GRASP (Nicholls, 1992). All views are in the same orientation.

Fig. 3 (A) Richardson representation of the canonical  $\alpha/\beta$  hydrolase fold.  $\beta$  strands are represented as arrows, while  $\alpha$  helices are rectangles. Secondary structural element numbering is according to the review by Schrag & Cygler (1997). Helix C, which immediately follows the “nucleophilic elbow”, is colored pink.  
(B) Richardson diagram of the cPLA<sub>2</sub> fold. The numbering scheme was devised so that the helix immediately following Ser288 of SEQ ID NO:2 is

Helix C, as in the canonical  $\alpha/\beta$  hydrolase fold. The central core is colored yellow for a more facile comparison with the canonical  $\alpha/\beta$  hydrolase fold in (A). Elements composing the “cap” are colored purple; loop regions in red are highly mobile and do not present traceable electron density.

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Fig. 4. Primary structure alignment of cPLA<sub>2</sub>  $\alpha$ ,  $\beta$ , and  $\gamma$ . Identical residues are boxed, while the secondary structural elements observed in the x-ray crystal structure of cPLA<sub>2</sub>  $\alpha$  are indicated below the sequences. Secondary structural elements outside of the cap region are shown in yellow, while those in the cap region are shown in purple. Black lines represent areas of turns or loops. Residues not identified with black lines or secondary structural elements do not display traceable electron density.

Fig. 5 (A). Surface diagram showing the catalytic domain of cPLA<sub>2</sub> covered by the lid residues. Ser228 of SEQ ID NO:2 is shown at the bottom of the funnel. The continuation of the sequence which is not visible in experimental maps is represented by red dots and is proposed to be involved in the formation of a lid hinge. Residues for which only the backbone atoms are visible in electron density maps are represented as alanines. Exposed surfaces of all hydrophobic residues have been colored blue, and that of Arg200 of SEQ ID NO:2 has been colored red. The figure was prepared with GRASP (Nicholls, 1992).

(B) Close-up of the active site of cPLA<sub>2</sub> in a 7 Å radius around Ser228 of SEQ ID NO:2. The two residues involved directly in catalysis are colored green. Arg200 of SEQ ID NO:2 and the loop harboring Gly residues 197 and 198 of SEQ ID NO:2 are shown in yellow. A single water molecule visible in the experimental maps hydrogen bonds with Asp549 of SEQ ID NO:2 and carbonyl atoms from Trp393 of SEQ ID NO:2 and Thr330 of SEQ ID NO:2. Figure generated with Molscript and RASTER3D.

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Fig. 6. Catalytic mechanism proposed for cPLA<sub>2</sub>, involving the attack of Ser228 of SEQ ID NO:2 on the *sn*-2 position of the glycerophospholipidic substrate. AA: arachidonic acid; HG: head group; C18: octadecyl group. Gly 197 of SEQ ID NO:2 and 198 of SEQ ID NO:2 are suggested as being part of the oxyanion hole, while Arg200 of SEQ ID NO:2 stabilizes the phosphate moiety of the head group.

#### Detailed Description of the Invention and Preferred Embodiments

The structure of cPLA<sub>2</sub> was solved by employing one heavy atom scatterer per 749 residues (corresponding to SEQ ID NO:2)

Full length human cPLA<sub>2</sub> was expressed in CHO cells and purified by modification of the methodology described in Clark et al., 1990 (Stahl et al., manuscript in preparation). Crystals were obtained at 18°C using PEG 1000 as a precipitant and employing standard vapor diffusion techniques. Single crystals grew within a few days to dimensions of up to 0.6 mm X 0.5 mm X 0.1 mm but were highly susceptible to x-ray damage. Rounds of crystal soaking into cryoprotectant solutions with increasing amounts of PEG 400 and DMSO, followed by flash cooling and exposure to synchrotron radiation, were critical in obtaining diffraction to a minimum Bragg spacing of 2.5 Å. Crystals are of space group P2<sub>1</sub>2<sub>1</sub>2 (a = 153.59 Å, b=95.49 Å, c=139.13 Å), with two monomers (1498 residues) and 60% solvent per asymmetric unit.

Attempts to prepare heavy atom soaked crystals of cPLA<sub>2</sub> revealed that only gadolinium or terbium could provide isomorphous derivatives. Either lanthanide, however, replaced a single Ca<sup>2+</sup> atom in CaLB, thus providing a single heavy atom scatterer per 749 amino acid residues. In-

house phasing information from these crystals was not of high enough quality to produce an initial electron density map. This observation, added to the fact that binding of most heavy atoms generated non-isomorphism between native and soaked crystals, led to an effort to solve the structure of cPLA<sub>2</sub> by multiwavelength anomalous dispersion (MAD) phasing (Hendrickson, 1991).

Terbium-soaked cPLA<sub>2</sub> crystals were prepared, cryotreated (see Methods), and cooled in a 100°K nitrogen stream. Data at three different wavelengths around the Tb L<sub>III</sub> edge (see Table I) were collected from a single crystal which, due to radiation sensitivity, was translated along its rotation axis between data collections. Experimental phases to 3.2Å were calculated with SHARP (de La Fortelle & Bricogne, 1997); subsequently, several cycles of solvent flattening and two-fold averaging in DM (Cowtan et al., 1996) allowed us to extend phases to 2.5Å. This procedure generated a high quality electron density map (Fig. 1) in which both domains of each cPLA<sub>2</sub> monomer could be clearly identified. Initially, CaLB (Perisic et al., 1998; 1RLW) was rotated into density and a polyalanine trace was built for the visible regions of the catalytic domain using the program QUANTA (Molecular Simulations Inc.) generating a model with approximately 550 residues for each monomer. Phase restrained refinement of this initial structure with a final phase combination step (REFMAC; Murshudov et al., 1997) followed by manual model building (QUANTA) generated a model which was subsequently refined in XPLOR (Brünger et al., 1992b). The present model contains 1285 residues (between both monomers) and 40 water molecules (Table I).

## Molecular structure

The cPLA<sub>2</sub> monomer is a two domain ellipsoidal structure with dimensions of ~ 100 Å X 55 Å X 45 Å (Fig. 2a). The N-terminal CaLB domain (residues 16-138 of SEQ ID NO:2) is a distinctly folded β sandwich, connected by residues 139-143 of SEQ ID NO:2 to the catalytic domain, with which it forms very few protein-protein contacts. The central core of the catalytic domain is composed of a 10-strand central β sheet with interspersed helices which is distinct from the canonical α/β hydrolase fold. The cPLA<sub>2</sub> monomers present in the asymmetric unit are not perfectly superimposable due to flexibility of the interdomain loop. Indeed, when the CaLB domains are superimposed, there is a 4-5° difference between the two catalytic domains. The loop which interconnects the domains has a distinct conformation in each monomer and its residues display high temperature factors.

cPLA<sub>2</sub> is a cytosolic protein which translocates to the membrane when free levels of Ca<sup>2+</sup> are raised to submicromolar levels (Clark et al., 1990, 1991). The domain arrangement of cPLA<sub>2</sub> suggests how the active site is oriented with respect to the cellular membrane. Fig. 2b is a surface diagram which highlights results of HSQC studies performed on CaLB by Xu and co-workers (1998). Residues which displayed N<sup>15</sup>/NH shifts upon incubation with dodecylphosphocholine micelles in these experiments are highlighted in purple. It is clear that the highlighted residues appear on the same face of the molecule as the active site. Consequently, if CaLB employs these residues to associate with a phospholipid membrane, the catalytic domain is roughly positioned to bind a phospholipid substrate in the active site. The flexibility of the linker between the two domains as well as the lack of major protein-protein interactions between them

suggests that a small rotation between domains can be accomplished for optimal interactions with the membrane.

As shown in the surface potential diagram in Fig. 2c, there exists a highly basic region which extends from the active site through a strip of positively charged residues on the  $\beta 3$  strand of CaLB. This basic characteristic would be expected of a region in the protein making multiple electrostatic contacts with the negatively-charged phospholipid head groups of the membrane layer (see below). Residues 434 to 456 of SEQ ID NO:2, however, are disordered, making it impossible to accurately define the true size of the basic patch. Nevertheless, it is noteworthy that similar basic patches were seen in PI4 kinase and in different species of sPLA<sub>2</sub>s (Rao et al., 1998). It is tempting to suspect that the high affinity binding of cPLA<sub>2</sub> to membranes made of phosphatidyl methanol liposomes (Hixon & Gelb, 1998) is mediated through this patch and the nearby basic stretch of  $\beta$  strand 3 in the CaLB domain.

#### The N-terminal CaLB domain

The structure of the CaLB domain in full-length cPLA<sub>2</sub> is very similar to those solved by NMR and x-ray crystallography (Xu et al., 1998; Perisic et al., 1998), with minor differences. Briefly, it consists of eight antiparallel  $\beta$  strands interconnected by six loops, folding into a  $\beta$ -sandwich which fits the "type II" topology for C2 domains (Nalefski et al., 1994b). Two Ca<sup>2+</sup> atoms are bound at one end of CaLB through a constellation of Asp and Asn side chains, as well as backbone carbonyl atoms, on three distinct loops (calcium-binding loops; CBLs); the same atomic arrangement has been observed in the CaLB domain solved by Perisic and co-workers (1998). The Ca<sup>2+</sup> atoms are approximately 4 Å apart. The environment of the Ca<sup>2+</sup> atoms in full-length cPLA<sub>2</sub>, however,



does not display any of the water molecules present in the CaLB structure solved by these authors; instead, coordinated to calcium site 1 (defined in Perisic et al., 1998) is a molecule of MES (2-[N-morpholino] ethanesulfonic acid) from the buffer employed in crystallization and cryoprotection. In  
5 both cPLA<sub>2</sub> monomers, the distance between Ca<sup>2+</sup> 1 and the closest MES sulfonate oxygen atom is approximately 2.2 Å. In addition, the morpholino group is also in contact with the side chains of His 62 of SEQ ID NO:2 and Tyr96 of SEQ ID NO:2, thus forming a small hydrophobic niche. Although a crystallization artifact, the coordination of Ca<sup>2+</sup> 1 of  
10 cPLA<sub>2</sub> to the sulfate of MES could be emulating the binding mode of the phosphate group of a phospholipid molecule, thus suggesting that, in cPLA<sub>2</sub>, Ca<sup>2+</sup> acts as a bridge between the protein and the phosphorylated membrane rather than solely as an allosteric activator.

15 The novel topology of the cPLA<sub>2</sub> fold distinguishes it from α/β hydrolases

The catalytic domain of cPLA<sub>2</sub> is composed of 14 β strands and 13 α helices; its central core consists of a 10-stranded central mixed β sheet surrounded by 9 α helices with strands β5 through β11 forming the most  
20 obvious portion of the sheet (refer to the Richardson diagram in Fig. 3b). The β sheet has a superhelical twist. For simplicity, the secondary elements of cPLA<sub>2</sub> have been identified based on the α/β hydrolase fold nomenclature presented by Schrag & Cylger (1997), in which the catalytic serine is always preceded by β5 and followed by Helix C.

25

The first β strand in the cPLA<sub>2</sub> core is β1, which follows the flexible connection after CaLB. A long loop containing one long helix makes the connection to β4, in the central part of the fold. This β1/α-helix construction is analogous to the one observed in *Humicola lanuginosa*  
30 lipase, where the helical region is also not considered part of the fold but

connects its  $\beta$ 10 to the first  $\beta$  strand in the core (entry 1TIB in the PDB). The following parallel  $\beta$  strand,  $\beta$ 5, precedes the catalytic serine (228 of SEQ ID NO:2). The topologies of  $\beta$ 5, Helix C (colored pink in Figs. 3a and 3b), and of the loop which connects them are similar in  $\alpha/\beta$  hydrolases.

5 This interconnecting loop is termed the “nucleophilic elbow. Three more  $\alpha$ -helices, interwoven by loops, provide the connection between this region and the further 4  $\beta$  strands of this part of the fold. Of the four  $\beta$  strands that follow ( $\beta$ 6- $\beta$ 9),  $\beta$ 6 is the longest, making few hydrogen bonds with  $\beta$ 7. Strands  $\beta$ 7 to  $\beta$ 1, therefore, although not contiguous in sequence, can be

10 considered a small  $\beta$  sheet within a larger structure.

After  $\beta$ 9 there is a major divergence from formation of the central  $\alpha/\beta$  core. The cPLA<sub>2</sub> sequence at this point forms the region shown in purple in Figs. 2a and 3b. This 180-residue patch forms a catalytic domain

15 “cap”. Asp549 of SEQ ID NO:2, the catalytic partner of Ser228 of SEQ ID NO:2, lies in the region between the end of the cap and  $\beta$ 10, which is part of the central core. Following the cap structure, the last three  $\beta$  strands are positioned as to complete the central  $\beta$  sheet and are interspersed by helices G to J.

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The  $\alpha/\beta$  hydrolase fold is common to many esterases and other hydrolytic enzymes (Schrag & Cygler, 1997). Its Richardson diagram (Fig. 3a) consists of a central  $\beta$  sheet whose order of  $\beta$  strands follows the sequence linearly (with the exception of  $\beta$ 3, which is often placed between

25  $\beta$ 4 and  $\beta$ 5). At first glance, the topology of cPLA<sub>2</sub> appears to be a circular permutation of the  $\alpha/\beta$  hydrolase fold. However, a careful comparison of Figs. 3a & 3b clearly reveals that only the region encompassing the nucleophilic elbow is in fact directly comparable ( $\beta$ 5 to Helix C; residues 222-238 of SEQ ID NO:2). Major distinctions include the antiparallel nature

30 of strands  $\beta$ 6 to  $\beta$ 9, the multiplicity of helices between  $\beta$ 5 and  $\beta$ 6, and the

absence of intervening helices between strands of the latter part of the cpla2  $\alpha/\beta$  core.

Although the cap structure in cPLA<sub>2</sub> (residues 370-548 of SEQ ID NO:2) is part of the catalytic domain, it is not included in the  $\alpha/\beta$  core. Sequence comparisons of the catalytic domains of human cPLA<sub>2</sub>s  $\alpha$ ,  $\beta$ , and  $\gamma$  (Fig. 4) show that homology is concentrated within the  $\alpha/\beta$  core (yellow elements) and  $\beta$  strands 9a and 9d. Thus, the central part of the cap is distinct among cPLA<sub>2</sub> isoforms. A comparison between the ribbon diagram of cPLA<sub>2</sub> in Fig. 2a, in which the cap region is displayed in purple, and the surface potential diagram in Fig. 2c, reveals that the highly basic region hypothesized above as making electrostatic contacts with membrane phospholipids is in fact formed in large part by cap residues.

The cap region of cPLA<sub>2</sub> also contains two of the three most mobile regions of the entire structure, residues 433-456 of SEQ ID NO:2 and 500-536 of SEQ ID NO:2 (the third region is the C-terminus, residues 728-749 of SEQ ID NO:2). These amino acid stretches do not have traceable electron density and are not included in the model (dotted lines in Fig. 2a). Interestingly, it is these highly flexible regions of the cap which harbor three of the four serine residues that become phosphorylated upon agonist stimulation (437, 454, 505 of SEQ ID NO:2). The role of Ser437 of SEQ ID NO:2 and Ser454 of SEQ ID NO:2 is unclear, since they are not conserved among different species. In contrast, Ser505 of SEQ ID NO:2 is conserved in cPLA<sub>2</sub> from evolutionarily distinct species (chicken, human, zebrafish, murine, rat), and its phosphorylation by MAP kinase is required for maximal activation of cPLA<sub>2</sub> in insect cells (Lin, et al., 1993; Qiu et al., 1998). Ser505 of SEQ ID NO:2, which in our crystals is likely to be heterogeneously phosphorylated and is located in a highly flexible, solvent exposed loop, makes no contacts either with the body of the protein or other neighboring cPLA<sub>2</sub> monomers in the lattice. Ser505 of SEQ ID NO:2

is distal to both the active site and the membrane-binding region (see Fig. 2a); nevertheless, its proximity to the hinge between CaLB and the catalytic domain is noteworthy (see discussion). The fourth site of cPLA<sub>2</sub> phosphorylation, Ser727 of SEQ ID NO:2, is at the C-terminus of the structure. Although this site is conserved among species, its functional relevance is not yet known.

The active site funnel is partially covered by a solvent-accessible lid

10        The most remarkable feature of the cPLA<sub>2</sub> structure is the active site funnel, which penetrates one third of the way into the catalytic domain to reveal Ser228 of SEQ ID NO:2 and Asp549 of SEQ ID NO:2 placed at the bottom of a deep, narrow cleft. Although wide at the top, the funnel narrows down to an approximate diameter of 7 Å at the mouth of the active site cleft visible in Fig. 5a. The funnel is lined with hydrophobic residues (blue in Fig. 5a) and forms a cradle into which fatty acyl moieties of membrane phospholipid substrates may bind.

20        The cPLA<sub>2</sub> active site is partially covered by a “lid” composed of residues 413-457 of SEQ ID NO:2. The lid folds into a loop region, followed by a small helical stretch and a short turn (see Figure 5a). Residues 408-412 of SEQ ID NO:2, which lead into the lid region, display very large temperature factors, and residues 434-456 of SEQ ID NO:2 do not possess traceable electron density. These observations suggest that these regions are highly mobile and could be envisioned as a “lid hinge”. The visible region of the lid has an amphipathic character; its solvent exposed face is formed primarily by polar residues (T416, E418, E419, E420, N423 of SEQ ID NO:2), while the inner side is lined with hydrophobic amino acids (M417, L421, I424 of SEQ ID NO:2). It is conceivable that the “double-sided” character of the lid comes into play upon membrane phospholipid

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binding, since one face has the capability of forming hydrogen-bonding contacts while the other is more apt for hydrophobic interactions, either with the substrate or the membrane.

5            Attempts to model a diacylphospholipid molecule in the active cleft of cPLA<sub>2</sub> with the lid in place demonstrated that the acyl ester bond cannot be positioned in the vicinity of the active site serine without the generation of clashes with surrounding residues. Consequently, it is conceivable that the generation of appropriate space for substrate binding requires lid  
10 movement, a proposal in agreement with the observation that cPLA<sub>2</sub> displays greater activity in the presence of micellular rather than monomeric substrates (Cygler & Schrag, 1997), a phenomenon known as interfacial activation.

15            Most lipases display interfacial activation as a result of a conformational rearrangement of a lid that covers the active site in the "closed" form of the enzyme. The lid moves away upon binding of micelles, thereby generating the "open" form, in which catalytic residues are exposed to the substrate. X-ray crystallography has yielded multiple  
20 examples of this activation mechanism through the determination of structures of lipases both in "closed" and "open" forms, the latter for the most part crystallized in the presence of inhibitors (Cygler & Schrag et al., 1997). It is probable that the interfacial activation mechanism of cPLA<sub>2</sub> is comparable to that of other lid-containing lipases, in that lid movement is a  
25 key step in increasing the accessible surface area of the active site funnel as well as providing unhindered access to the catalytic residues.

## The cPLA<sub>2</sub> active site contains a catalytic dyad

Acyl hydrolysis by  $\alpha/\beta$  hydrolases is performed by a (Ser-Asp/Glu-His) catalytic triad reminiscent of the one present in serine proteases. The substrate's acyl ester bond is attacked by the nucleophilic serine, generating a covalently bound acyl-enzyme intermediate that is subsequently released following a step that involves the attack of a water molecule. Although all lipid-metabolizing enzymes with the  $\alpha/\beta$  hydrolase fold proceed via the use of a catalytic triad, the identification of all members of such a triad in cPLA<sub>2</sub> proved to be a challenging task. Site-directed mutagenesis by Sharp and co-workers (1994) confirmed the role of Ser228 of SEQ ID NO:2 and Asp549 of SEQ ID NO:2 in catalysis; the failure of any of the 19 histidine residues to affect activity, however, pointed to a novel catalytic mechanism (Pickard et al., 1996). These observations led many to propose that cPLA<sub>2</sub> contains a novel catalytic center which does not require the participation of histidine, while the relevance of Arg200 of SEQ ID NO:2 for activity remained unknown (Leslie, 1997; Pickard et al., 1996).

The x-ray crystal structure of cPLA<sub>2</sub> clearly reveals an active site in which Ser228 of SEQ ID NO:2 sits at the bottom of a funnel-shaped cavity; the O $\square$ 2 of Asp549 of SEQ ID NO:2 lies at a distance of 2.9 Å from its O $\square$  atom (Fig. 5b). It is clear, however, that the active site of cPLA<sub>2</sub> lacks a histidine residue. In addition, there are no other residues in a 6 Å range that could fulfill the function of active site base. All polar contributions in a range of 3.5 Å away from either residue are made by backbone groups or by a lone water molecule positioned 3.2 Å away from the O $\square$ 1 atom of Asp549 of SEQ ID NO:2. Although Asn555 of SEQ ID NO:2 lines the active site funnel, its N $\square$ 2 atom is approximately 6 Å away from either residue and would not be the ideal candidate to fulfill this function.

In acyl hydrolases, upon attack on the *sn*-2 position of a glycerophospholipidic substrate, the transition state requires stabilization by an "oxyanion hole", or a set of hydrogen bond donors (usually amide atoms) and/or basic residues with the function of stabilizing the developing negative charge of the transition state. In several lipases, at least one of the residues which contribute to the oxyanion hole is part of a moving loop, and the proper conformation is only attained when the lipase is in "open" form; this rearrangement, however, is not an absolute requirement. In cPLA<sub>2</sub>, Gly197 and 198 of SEQ ID NO:2 are part of a glycine-rich flexible loop between  $\beta$ 4 and Helix B; this positioning allows the amide backbones of Gly197 of SEQ ID NO:2 and Gly198 of SEQ ID NO:2 to be good candidates for members of a pre-formed oxyanion hole (see Fig. 5b). In addition, the backbone amide group of Gly229 of SEQ ID NO:2, which is at the apex of the turn between  $\beta$ 5 and Helix C, also points in the direction of the Gly197 of SEQ ID NO:2 loop and therefore may also be part of the hole. Consequently, this region, much like the oxyanion hole in chymotrypsin, appears to be well-designed to stabilize the tetrahedral intermediate generated by the nucleophilic attack of the ester.

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A multiplicity of roles has been suggested for Arg200 of SEQ ID NO:2. It has been implicated in providing assistance to CaLB in binding the enzyme to the lipid interface; interacting with the phospholipid membrane; participating as a catalytic residue; stabilizing an acyl-enzyme intermediate: or associating with the phosphoryl group of the substrate phospholipid (Pickard et al., 1996). The positioning of Arg200 of SEQ ID NO:2 imbedded within the funnel (its surface area is colored red in Fig. 5a) precludes it from providing any lipid binding assistance to CaLB. In addition, its side chain is approximately 9 Å away from the active site serine, which prevents it from playing a role in catalysis. Arg200 of SEQ ID

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NO:2, however, makes several key contacts with residues around the active site funnel. The side chain makes a salt bridge with Thr680 of SEQ ID NO:2 and contacts backbone atoms of Phe678 of SEQ ID NO:2, both of which lie in the loop between helices H and I. The location of Arg200 of SEQ ID  
5 NO:2 on the oxyanion hole loop suggests that the lack of these two hydrogen bonds in the Arg200 Lys mutant reported by Pickard & co-workers (1996) could be responsible for subtle alterations on the conformation of the oxyanion hole loop with dramatic consequences on activity.

10

Catalysis by cPLA<sub>2</sub> proceeds via a mechanism distinct from that of other acyl hydrolases

The absence of a histidine residue or any other potential base in the:  
15 active site of cPLA<sub>2</sub> suggests that the enzyme promotes acyl hydrolysis via a novel catalytic mechanism. In serine proteases and other hydrolases, a histidine residue accepts a proton from the hydroxyl group of the reactive serine, thus facilitating formation of the covalent tetrahedral intermediate. In a second step, the acyl-enzyme intermediate is hydrolyzed by a water  
20 molecule to release the product, restoring the ser-hydroxyl to the enzyme. Class A TEM-1  $\beta$  lactamase, whose catalytic pathway also involves the acylation of an active site serine followed by the hydrolysis of the ester bond, transfers a proton from the active site Ser70 of SEQ ID NO:2 to the carboxylate group of Glu166 of SEQ ID NO:2, either directly (Gibson et al.,  
25 1990) or via a water molecule (Lamotte-Brasseur et al., 1991). More recent studies (Damblon et al., 1996) have suggested that the long distance between the carboxylate oxygens of Glu166 of SEQ ID NO:2 and Ser70 of  
SEQ ID NO:2 precludes direct proton transfer, but propose the participation of a bridging water molecule for proton relay. In the catalytic  
30 mechanism of penicillin acylase (Duggleby et al., 1995), which contains a



single residue catalytic center composed of the N-terminal serine, a bridging water mediates the basic character of the  $\alpha$ -amino group of Ser1 of SEQ ID NO:2. As a consequence, the O $\gamma$  atom of Ser1 of SEQ ID NO:2 has its nucleophilicity sufficiently enhanced by the amino-terminal group, and  
5 formation of the acyl-enzyme intermediate ensues.

In cPLA<sub>2</sub>, the only residue capable of playing the role of general base is Asp549 of SEQ ID NO:2 since there are no other side chains in a radius of 3.5 Å of the O $\gamma$  atom of Ser228 of SEQ ID NO:2. Fig. 6 displays a  
10 proposed model for the catalytic mechanism of cPLA<sub>2</sub>. Once the enzyme is bound to the membrane, a single phospholipid molecule binds at the active site. The phosphate moiety of the head group (HG in Fig. 6) is stabilized by the Arg200 of SEQ ID NO:2 side chain. An oxyanion hole formed by the backbone amide groups of Gly197 of SEQ ID NO:2 and Gly198 of SEQ ID  
15 NO:2 is also shown polarizing the *sn*-2 ester and stabilizing the tetrahedral intermediate formed in panel B. Following formation of the enzyme-substrate complex, Asp549 of SEQ ID NO:2 acts as the catalytic base and abstracts a proton from the hydroxyl group of the reactive Ser228 of SEQ ID NO:2, which attacks the *sn*-2 ester and forms the acyl enzyme via the  
20 stabilized tetrahedral intermediate. The acyl enzyme is subsequently hydrolyzed by a water molecule (panel C) to yield free lyso-phospholipid and, after collapse of the double bond of the arachidonyl intermediate, free arachidonic acid (AA in Fig. 6; panels D and E). cPLA<sub>2</sub> may then dissociate from the membrane interface or bind another phospholipid substrate and  
25 repeat the cycle. Thus, cPLA<sub>2</sub> is a third distinct example of an acylase which uses a nucleophilic serine without a complete catalytic triad.

## Discussion

Despite the large asymmetric unit (1498 amino acids) and the fragility of cPLA<sub>2</sub> crystals, MAD phasing was successful in producing a high quality electron density map from data obtained from a single crystal.

5 Central to this success were the large Bijvoet and dispersive differences typical of the L<sub>III</sub> edge of a lanthanide atom, coupled to the high flux and wavelength stability of the Advanced Light Source (Berkeley, CA). With the advent of third generation synchrotrons, MAD should be routinely employed for the solution of large macromolecular structures.

10

cPLA<sub>2</sub> is essential for the biosynthesis of lipid mediators of inflammation, as demonstrated by the use of cPLA<sub>2</sub> deficient mice (Bonventre et al., 1997; Uozumi et al., 1997). Since leukotrienes, prostaglandins and PAF play significant roles in the pathophysiology of  
15 diseases of major public impact, it is imperative to understand how their biosynthesis is regulated. The structure of cPLA<sub>2</sub> provides new insights into the origin of arachidonyl selectivity and the regulation by phosphorylation. In addition, it identifies both a new fold and mechanism for lipases. The structure of cPLA<sub>2</sub> is only the second one in which a C2  
20 domain is seen in the context of the entire protein. Significant differences are seen between PLC $\delta$ 1 and cPLA<sub>2</sub>.

The cPLA<sub>2</sub> fold clearly shows that the enzyme consists of two distinct, independently folded domains. This result was not unexpected  
25 based on earlier work in which the CaLB and catalytic domains were fully functional when expressed independently. However, what was surprising was the sparsity of contacts and potential flexibility between the domains. Although C2 domains are commonly observed in signaling molecules, to date only the crystal structure of PLC $\delta$ 1 has reported a C2 domain present  
30 in the context of the catalytic domain (Essen et al., 1996). In this case,

extensive hydrophobic contacts exist between almost the entire surface of one face of the C2 domain and the catalytic domain. In contrast, the interactions between the catalytic and CaLB domains of cPLA<sub>2</sub> are sufficiently limited that the conformations of the polypeptide linking the two in the different monomers of the asymmetric unit are distinct. This observation is of mechanistic importance in that the optimal orientation of the CaLB and catalytic domains is not fixed, but instead may be regulated in some fashion. It is interesting to note that although the region of the protein including Ser-505 of SEQ ID NO:2, which is essential for optimal activity in cells, is disordered, this important MAP-kinase site located near the hinge region.

The detailed comparison of the structure of cPLA<sub>2</sub> and the classic  $\alpha/\beta$  hydrolase fold clearly argues that cPLA<sub>2</sub> contains a novel topology. However, as noted earlier, the  $\beta$  hairpin containing the active site serine is structurally analogous to “nucleophilic elbow” of the  $\alpha/\beta$  hydrolase fold. A Blast search of the cPLA<sub>2</sub> catalytic domain shows an extended region of homology among PLBs and cPLA<sub>2</sub>  $\alpha$ ,  $\beta$  and  $\gamma$  which includes -residues ~190-232 of SEQ ID NO:2. This homology is of functional significance in that it contains Arg 200 of SEQ ID NO:2, the backbone regions comprising the oxyanion hole as well as the novel GXXS lipase motif in which the second serine replaces the classic glycine. The “concentration” of homology in the short region is also explained by the genomic structure, where these residues are encoded by a single exon (which corresponds to residues 186-238 of SEQ ID NO:2).

Instead of containing a catalytic triad of Ser, His, Asp/Glu as seen for the  $\alpha/\beta$  hydrolases, cPLA<sub>2</sub> cleaves the *sn*-2 ester using a dyad composed of Ser-228 of SEQ ID NO:2 and Asp-549 of SEQ ID NO:2. The carboxylate of Asp-549 of SEQ ID NO:2 is the only residue in sufficiently close

proximity to activate the serine for nucleophilic attack. A similar catalytic dyad has been proposed for the amide hydrolysis reaction catalyzed by the Class A  $\beta$ -lactamases (Matagne et al., 1998). In this case, however, the glutamate side chain activates the serine residue via an intervening water molecule. Although it is difficult to assess the comparable efficiency of a dyad vs. a triad, it is noteworthy that it is the activation energy required to reach the transition state which is important in catalysis. Therefore, the stabilization due to an effective oxyanion hole can offset a less nucleophilic serine. In this crystal structure, the backbone amide group of glycines 197 of SEQ ID NO:2 and 198 of SEQ ID NO:2, positioned a mere two residues from the critical Arg-200 of SEQ ID NO:2, are appropriately positioned to act as the oxyanion hole. The backbone NH of Gly-229 of SEQ ID NO:2 could possibly also aid in stabilizing the oxyanion developing in the transition state and present in the tetrahedral intermediates. The effectiveness of the oxyanion hole is consistent with NMR studies where arachidonyltrifluoromethyl ketone appeared to bind to the enzyme as the ionized hemiketal.

The catalytic serine of cPLA<sub>2</sub> is present in a deep funnel near the center of the catalytic domain. Attempts to model the phospholipid into the active site demonstrated that the current conformation of the active site funnel was not large enough. Therefore, we propose that the somewhat mobile lid, whose C-terminus is linked to a completely disordered stretch of 23 amino acids, may move upon membrane binding, thus providing a larger accessible volume near the top of the funnel to accommodate the substrate. The crystal structures of pancreatic lipase/colipase both in the presence and absence of substrate/detergent micelles provide precedent for this model (van Tilbeurgh et al., 1993). In this case, a dramatic conformational change occurs in the presence of micelles or inhibitors entailing a lid movement of

as much as 29 Å to expose the active cleft and a hydrophobic patch. Such large structural modifications have been noted for other hydrolase proteins. This conformational change upon membrane surface binding has been used to explain the process of interfacial activation, in which the catalytic activity of a lipase is orders of magnitude greater toward a substrate presented in a micelle rather than as a monomer.

In the case of cPLA<sub>2</sub>, its lysophospholipase has been used compare its activity toward the same substrate presented either as a monomer or as part of a micelle. Such measurements have revealed that cPLA<sub>2</sub> activity increases ~1500-fold as the concentration of 1-palmitoyl-2-lysophosphatidylcholine increases by only 10-fold; thus, cPLA<sub>2</sub> is much more active toward substrates presented as a surface. Our structure suggests that a conformational change, dictated by movement of the flexible lid, occurs upon membrane binding; this observation is consistent with the previously observed interfacial activation.

In addition to the movement of lids covering the active sites, several structures have shown that the oxyanion hole that stabilizes the transition state is only fully formed in the presence of bound substrate or inhibitor (Cygler & Schrag, 1997). Cutinase is an exception to this general rule in that the oxyanion hole is fully formed in the native structure. Importantly, cutinase does not show interfacial activation (Martinez et al., 1992).

The selectivity of cPLA<sub>2</sub> for arachidonyl-containing phospholipids is a distinguishing feature. The low molecular weight sPLA<sub>2</sub>s do not distinguish among different fatty acids, whereas cPLA<sub>2</sub> shows high selectivity for arachidonyl and other fatty acids with cis-double bonds at the 5 and 8 positions in numerous assay formats (Clark et al., 1995; Gelb aasn-1 and sn-2, Gelb hydrazin). Prior to the determination of the

structure, the origin of cPLA<sub>2</sub> selectivity was unknown. It was conceivable that the catalytic machinery was located near the surface of the enzyme where it could act on the *sn*-2 ester without extracting the lipid from the bilayer. This would be analogous to the flattened kinase domain of PI4 kinase where the enzyme is thought to work on the lipid headgroup without extracting the phospholipid itself (Rao et al., 1998). In the case of cPLA<sub>2</sub>, we would anticipate the selectivity to be due to greater exposure of the *sn*-2 ester due to looser packing of the polyunsaturated fatty acid. However, as we see in the structure, the phospholipid must bind ~ 8-10 Å into the deep active site. Thus the selectivity must be due to interactions between the arachidonyl moiety and enzyme. It will be informative to mutate the residues which are distinct between □ and □ cPLA<sub>2</sub>s, namely in the active site and the completely non-conserved lid region, to determine differences in selectivity.

15

#### Preferred Methods of Administration and Dosing of Substances Identified in Accordance with the Invention

As used herein, "phospholipase enzyme activity" means positive activity in an assay for metabolism of phospholipids (preferably one of the assays described in Example 2 below or described in any of the references incorporated herein). A compound has "phospholipase enzyme inhibiting activity" when it inhibits the activity of a phospholipase (preferably cPLA<sub>2</sub>) in any available assay (preferably an assay described below in Example 70) for enzyme activity. In preferred embodiments, a compound has (1) an IC<sub>50</sub> value of less than about 25 μM in the LysoPC assay; (2) an IC<sub>50</sub> value of less than about 50 μM in the vesicle assay; and/or (3) an IC<sub>50</sub> value of less than about 1 μM in the PMN assay.

Compounds of the present invention and ursolic acid are useful for inhibiting phospholipase enzyme (preferably cPLA<sub>2</sub>) activity and, therefore, are useful in "treating" (i.e., treating, preventing or ameliorating) inflammatory or inflammation-related conditions (e.g., rheumatoid arthritis, psoriasis, asthma, inflammatory bowel disease, and other diseases mediated  
5 by prostaglandins, leukotrienes or PAF) and other conditions, such as osteoporosis, colitis, myelogenous leukemia, diabetes, wasting and atherosclerosis.

The present invention encompasses both pharmaceutical  
10 compositions and therapeutic methods of treatment or use which employ compounds of the present invention.

Compounds of the present invention may be used in a pharmaceutical composition when combined with a pharmaceutically acceptable carrier. Such a composition may also contain (in addition to a  
15 compound or compounds of the present invention and a carrier) diluents, fillers, salts, buffers, stabilizers, solubilizers, and other materials well known in the art. The term "pharmaceutically acceptable" means a non-toxic material that does not interfere with the effectiveness of the biological activity of the active ingredient(s). The characteristics of the carrier will  
20 depend on the route of administration. The pharmaceutical composition of the invention may also contain cytokines, lymphokines, or other hematopoietic factors such as M-CSF, GM-CSF, IL-1, IL-2, IL-3, IL-4, IL-5, IL-6, IL-7, IL-8, IL-9, IL-10, IL-11, IL-12, G-CSF, Meg-CSF, stem cell factor, and

erythropoietin. The pharmaceutical composition may further contain other anti-inflammatory agents. Such additional factors and/or agents may be included in the pharmaceutical composition to produce a synergistic effect with compounds of the present invention, or to minimize side effects caused  
5 by the compound of the present invention. Conversely, compounds of the present invention may be included in formulations of the particular cytokine, lymphokine, other hematopoietic factor, thrombolytic or anti-thrombotic factor, or anti-inflammatory agent to minimize side effects of the cytokine, lymphokine, other hematopoietic factor, thrombolytic or anti-thrombotic  
10 factor, or anti-inflammatory agent.

The pharmaceutical composition of the invention may be in the form of a liposome in which compounds of the present invention are combined, in addition to other pharmaceutically acceptable carriers, with amphipathic agents such as lipids which exist in aggregated form as micelles, insoluble  
15 monolayers, liquid crystals, or lamellar layers in aqueous solution. Suitable lipids for liposomal formulation include, without limitation, monoglycerides, diglycerides, sulfatides, lysolecithin, phospholipids, saponin, bile acids, and the like. Preparation of such liposomal formulations is within the level of skill in the art, as disclosed, for example, in U.S. Patent No. 4,235,871; U.S.  
20 Patent No. 4,501,728; U.S. Patent No. 4,837,028; and U.S. Patent No. 4,737,323, all of which are incorporated herein by reference.

As used herein, the term "therapeutically effective amount" means the total amount of each active component of the pharmaceutical composition or



method that is sufficient to show a meaningful patient benefit, i.e., treatment, healing, prevention or amelioration of an inflammatory response or condition, or an increase in rate of treatment, healing, prevention or amelioration of such conditions. When applied to an individual active  
5 ingredient, administered alone, the term refers to that ingredient alone. When applied to a combination, the term refers to combined amounts of the active ingredients that result in the therapeutic effect, whether administered in combination, serially or simultaneously.

In practicing the method of treatment or use of the present invention,  
10 a therapeutically effective amount of a compound of the present invention is administered to a mammal having a condition to be treated. Compounds of the present invention may be administered in accordance with the method of the invention either alone or in combination with other therapies such as treatments employing other anti-inflammatory agents, cytokines,  
15 lymphokines or other hematopoietic factors. When co-administered with one or more other anti-inflammatory agents, cytokines, lymphokines or other hematopoietic factors, compounds of the present invention may be administered either simultaneously with the other anti-inflammatory agent(s), cytokine(s), lymphokine(s), other hematopoietic factor(s),  
20 thrombolytic or anti-thrombotic factors, or sequentially. If administered sequentially, the attending physician will decide on the appropriate sequence of administering compounds of the present invention in combination with other anti-inflammatory agent(s), cytokine(s),

lymphokine(s), other hematopoietic factor(s), thrombolytic or anti-thrombotic factors.

Administration of compounds of the present invention used in the pharmaceutical composition or to practice the method of the present invention can be carried out in a variety of conventional ways, such as oral  
5 ingestion, inhalation, or cutaneous, subcutaneous, or intravenous injection.

When a therapeutically effective amount of compounds of the present invention is administered orally, compounds of the present invention will be in the form of a tablet, capsule, powder, solution or elixir. When  
10 administered in tablet form, the pharmaceutical composition of the invention may additionally contain a solid carrier such as a gelatin or an adjuvant. The tablet, capsule, and powder contain from about 5 to 95% compound of the present invention, and preferably from about 25 to 90% compound of the present invention. When administered in liquid form, a liquid carrier such  
15 as water, petroleum, oils of animal or plant origin such as peanut oil, mineral oil, soybean oil, or sesame oil, or synthetic oils may be added. The liquid form of the pharmaceutical composition may further contain physiological saline solution, dextrose or other saccharide solution, or glycols such as ethylene glycol, propylene glycol or polyethylene glycol. When  
20 administered in liquid form, the pharmaceutical composition contains from about 0.5 to 90% by weight of compound of the present invention, and preferably from about 1 to 50% compound of the present invention.

When a therapeutically effective amount of compounds of the present invention is administered by intravenous, cutaneous or subcutaneous injection, compounds of the present invention will be in the form of a pyrogen-free, parenterally acceptable aqueous solution. The preparation of  
5 such parenterally acceptable protein solutions, having due regard to pH, isotonicity, stability, and the like, is within the skill in the art. A preferred pharmaceutical composition for intravenous, cutaneous, or subcutaneous injection should contain, in addition to compounds of the present invention, an isotonic vehicle such as Sodium Chloride Injection, Ringer's Injection,  
10 Dextrose Injection, Dextrose and Sodium Chloride Injection, Lactated Ringer's Injection, or other vehicle as known in the art. The pharmaceutical composition of the present invention may also contain stabilizers, preservatives, buffers, antioxidants, or other additives known to those of skill in the art.

15 The amount of compound(s) of the present invention in the pharmaceutical composition of the present invention will depend upon the nature and severity of the condition being treated, and on the nature of prior treatments which the patient has undergone. Ultimately, the attending physician will decide the amount of compound of the present invention with  
20 which to treat each individual patient. Initially, the attending physician will administer low doses of compound of the present invention and observe the patient's response. Larger doses of compounds of the present invention may be administered until the optimal therapeutic effect is obtained for the

patient, and at that point the dosage is not increased further. It is contemplated that the various pharmaceutical compositions used to practice the method of the present invention should contain about 0.1  $\mu$ g to about 100 mg (preferably about 100 :g to about 50 mg, more preferably about 100 :g to  
5 about 5 mg) of compound of the present invention per kg body weight.

The duration of intravenous therapy using the pharmaceutical composition of the present invention will vary, depending on the severity of the disease being treated and the condition and potential idiosyncratic response of each individual patient. It is contemplated that the duration of  
10 each application of the compounds of the present invention will be in the range of 12 to 24 hours of continuous intravenous administration. Ultimately the attending physician will decide on the appropriate duration of intravenous therapy using the pharmaceutical composition of the present invention.

15

### Example 1

Protein production, crystallization and data collection.

20 Full-length human cPLA<sub>2</sub> (residues 1 - 749 of SEQ ID NO:2) was cloned into vector pMT2-EMC-cPLA<sub>2</sub> and transfected into CHO cells. The resulting cell line, E5-CHO, was grown in  $\alpha$  medium (Gibco) containing 10% (v/v) dialyzed fetal calf serum and 10  $\mu$ M methotrexate as described in Lin et al. (1992). The cell pellet was typically lysed in pH 9.0 buffer and  
25 cPLA<sub>2</sub> in the supernatant was subsequently precipitated with (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>.

Multiple steps including affinity and size exclusion chromatography yielded protein samples which were suitable for crystallization experiments. A typical yield from a 100g pellet would be 15-25 mg of pure cPLA<sub>2</sub>.

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Crystals of cPLA<sub>2</sub> were obtained by vapor diffusion at 18°C using PEG 1000 as a precipitant using 12 mg/ml protein. Typically, plate-like crystals appeared overnight and continued to grow to a maximum size of 0.6 mm X 0.5 mm X 0.1 mm within one week. Native and heavy atom-soaked  
10 crystals were cryoprotected by transferring into increasing amounts of PEG 400 and DMSO. Heavy atom-modified crystals were prepared by soaking native crystals overnight in cryosolution with CaCl<sub>2</sub> replaced by 250 µM GdCl<sub>2</sub> or TbCl<sub>2</sub>. Cryoprotected crystals were flash cooled in a liquid nitrogen stream at 100 K prior to data collection.

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Diffraction data of the native, Gd- and Tb-soaked cPLA<sub>2</sub> crystals were collected at beamline 5.0.2 at Advanced Light Source using a Quantum 4 CCD detector (Area Detector Systems). Due to crystal sensitivity, the first image of each data set was analyzed with STRATEGY  
20 (R. Ravelli) in an effort to calculate the minimum amount of data collection required for a complete data set. After the determination of the optimal starting point, data was collected through a 90° sweep, after which the crystals were rotated to a position 180° from the starting point and a second 90° sweep was collected with a view towards maximizing Bijvoet  
25 pair accumulation. Crystals started displaying radiation sensitivity after approximately 100° of data collection, making it necessary to translate them along the rotation axis between wavelength changes. This methodology proved to be successful in that data sets collected from three different wavelengths displayed similar statistics. All data were collected  
30 at 100K and processed with DENZO/SCALEPACK (Otwinowski, 1993).

Heavy atom sites - Both Tb sites were identified by visual inspection of anomalous Patterson maps using diffraction data collected at the peak wavelength of the Tb L<sub>III</sub> edge (see Table I), confirming results from  
5 previous lower resolution Tb and Gd data sets collected on an in-house Raxis IV detector (Molecular Structure Corp.). Heavy atom parameter refinement and phasing were accomplished with SHARP (de la Fortelle & Bricogne, 1997). Density modification was performed in SOLOMON (CCP4) as implemented in SHARP. The high quality experimental 3.2 Å  
10 electron density map allowed for the positioning of the entire CaLB domain as well as the initial tracing and sequence assignment of the catalytic domain (QUANTA); this procedure facilitated the calculation of a mask encompassing the protein region, which was included in further calculations. These included histogram matching (Zhang and Main, 1990),  
15 two-fold non-crystallographic symmetry averaging, and phase extension from 3.2 to 2.5 Å using the native diffraction data in DM (Cowtan et al., 1996). Cycles of phase combination and refinement were performed with REFMAC (Murshudov et al., 1997), generating a map in which most of the model could be identified, including central residues of the flexible lid.  
20  
Refinement - Cycles of rebuilding as well as positional and thermal parameter refinement in XPLOR (Brünger, 1992b) were used to improve the model, which was submitted to simulated annealing refinement (12 - 2.5 Å) after the R<sub>free</sub> had dropped below 32% (Brünger et al., 1992a).  
25 Subsequent model-building stages were performed with the aid of omit maps generated through maximum-likelihood refinement as implemented in BUSTER (Bricogne, 1993). Refinement also included a uniform bulk solvent correction (B<sub>sol</sub>=23.8 Å<sup>2</sup>; k<sub>sol</sub>=0.305 e<sup>-</sup>/Å<sup>3</sup>) and the application of non-crystallographic symmetric restraints. All diffraction data with F > 2.0  
30 were used throughout the refinement except for a 10% randomly selected

test set which was used for calculation of R<sub>free</sub>. Fo-Fc maps were used to locate water molecules, which were placed at sites which displayed densities > 3.0  $\sigma$  and exhibited reasonable protein-solvent hydrogen-bonding distances without steric conflict. The final model contains 1285  
5 residues (molecule A: 9-433, 456-500, and 537-727 of SEQ ID NO:2) and 40 water molecules, and exhibits good stereochemistry, with an average bond length and bond-angle deviation from ideal geometry of 0.010 Å and 1.38°, respectively. The overall free R-value is 29.7% and the R value is 24.3% using diffraction data between 12 and 2.5 Å (Table I).

TABLE I

Statistics for data collection, phase determination and refinement

Data collection	Native	Peak	Inflection	Descending edge
Wavelength (Å)	$\lambda=1.20$	$\lambda_1=1.64902$	$\lambda_2=1.64963$	$\lambda_3=1.64834$
Max. resolution (Å)	2.5	3.4	3.3	3.2
Rsym (%)	6.4 (30.0)	11.2 (41.5)	10.3 (37.1)	9.0 (38.6)
% completeness	93.3 (87.9)	99.6 (99.4)	99.7 (99.5)	99.6 (99.5)
Total reflections	271686	195666	213851	233142
Unique reflections	66223	54331 <sup>e</sup>	59265 <sup>f</sup>	64885 <sup>e</sup>
$\langle I/\sigma(I) \rangle$	18.2 (3.3)	9.9 (2.6)	12.3 (3.3)	13.3 (2.8)
$f'$ (e <sup>-</sup> )		-9.89	-17.50	-1.86
$f''$ (e <sup>-</sup> )		31.90	18.63	19.24
<b>MAD phasing</b>				
Resolution limits (Å)	9.67	6.70	5.44	4.69
				4.18
				3.81
				3.53
				3.37
				overall
<b>Phasing power</b>				
$\lambda_2$	3.26	4.08	3.65	2.84
				2.07
				1.48
				1.11
				0.93
				2.24
$\lambda_1$ isomorphous	1.20	1.15	1.05	0.83
				0.75
				0.68
				0.63
				0.53
				0.83
$\lambda_1$ anomalous	3.25	4.26	3.89	3.18
				2.37
				1.70
				1.30
				1.21
				2.59
$\lambda_3$ isomorphous	0.98	1.20	1.24	1.32
				1.39
				1.35
				1.28
				1.30
$\lambda_3$ anomalous	3.18	4.01	3.58	2.99
				2.30
				1.66
				1.26
				1.07
				2.34
mean FOM	0.77	0.75	0.70	0.63
				0.55
				0.44
				0.35
				0.29
				0.51



### Model refinement

Resolution (Å)	12.0-2.5
Rfactor (%)	24.3
Rfree (%)	29.7
<B-value> (Å <sup>2</sup> )	40.7
<u>R.m.s deviations from ideal geometry</u>	
Bonds (Å)	0.007
Angles (°)	1.38
B-values (Å <sup>2</sup> )	8.6

$R_{\text{sym}} = \sum |I_h - \langle I_h \rangle| / \sum I_h$  where  $\langle I_h \rangle$  is the average intensity over symmetry equivalents.

£ Friedel pairs separate.

5 Phasing power =  $\sum |F_H| / \sum ||F_{PH\text{obs}}| - |F_{PH\text{calc}}||$ .

$R = \sum ||F_o| - |F_c|| / \sum |F_o|$ , where Rfree is calculated for a randomly chosen 10% of reflections and Rfactor is calculated for the remaining 90% of reflections ( $F > 2.0$ ) used for structure refinement.

10 Coordinates will be deposited at the Brookhaven Protein Databank and are included in Table 2.

## Example 2

### 15 Activity Assays

#### (a) Vesicle Assay

1-palmitoyl-2-[ $^{14}\text{C}$ ] arachidonyl phosphatidylcholine (58 mCi/mmol) (final concentration 6  $\mu\text{M}$ ) and 1,2-dioleoylglycerol (final concentration 3  $\mu\text{M}$ ) were mixed and dried under a stream of nitrogen. To the lipids was added 50 mM Hepes pH 7.5 (2x final concentration of lipids) and the suspension was sonicated for 3 min. at 4°C. To the suspension was added 50 mM Hepes pH 7.5, 300 mM NaCl, 2 mM DTT, 2 mM  $\text{CaCl}_2$  and 2 mg/ml bovine serum albumin (BSA) (Sigma A7511) (1.2x final concentration of lipids). A typical assay consisted of the lipid mixture (85  $\mu\text{l}$ ) to which was added consecutively, the inhibitor (5  $\mu\text{l}$  in DMSO) and cPLA<sub>2</sub>, 10 ng for an automated system or 1 ng for a manual assay, in 10  $\mu\text{l}$  of the BSA buffer. This assay was conducted by either the manual assay or automated assay protocol described below.

——(b) Soluble Substrate Assay (LysoPC)

1-[<sup>14</sup>C]-palmitoyl-2-hydroxyphosphotidyl-choline (57 mCi/mmol) (final concentration 4.4 μM) was dried under a stream of nitrogen. The lipid was resuspended by vortexing 80 mM Hepes pH 7.5, 1 mM EDTA (1.2 x final concentration). A typical assay consisted of lipid suspension (85 μl) to which was added consecutively the inhibitor (5 μl in DMSO) and cPLA<sub>2</sub>, 200 ng in 80 mM Hepes pH 7.5, 2 mM DTT and 1 M EDTA. This assay was conducted by either the manual assay or automated assay protocol described below.

10 (c) Automated Assay

The lipid suspension and inhibitor were pre-incubated for 7 min. at 37°C. Enzyme was added and the incubation was continued for a further 30 mins. The reaction was then quenched by the addition of decane: isopropanol: trifluoroacetic acid (192:8:1 w/v, 150 μl). A portion of the quench layer (50 μl) was passed through a Rainin Spheric-5 silica column (5 μ, 30 x 2.1 mm) eluting with heptane:methanol:TFA (97:3:0.1 v/v). The level of [<sup>14</sup>C]-arachidonic acid was analyzed by an in-line Radiomatic Flo-One/Beta counter (Packard).

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\_\_\_\_(d) Manual Assay

The lipid, inhibitor and enzyme mixture were incubated at 37°C for 30 min. The reaction was quenched by the addition of heptane:isopropanol:0.5M sulfuric acid (105:20:1 v/v, 200 µl). Half of the  
5 quench layer was applied to a disposable silica gel column (Whatman SIL, 1 ml) in a vacuum manifold positioned over a scintillation vial. Free [<sup>14</sup>C]-arachidonic acid was eluted by the addition of ethyl ether (1 ml). The level of radioactivity was measured by liquid scintillation counter.

10 (e) PMN Assay

PMNs were isolated using Ficoll-Hypaque according to the manufacturers directions. Red blood cells contaminating the PMNs were removed by hypotonic lysis, and the PMN pellet was washed once, and resuspended in Hanks buffered saline at a concentration of 2 x 10<sup>6</sup> cells/ml.  
15 The cells were preincubated with inhibitors for 15 min at 37°C and then stimulated with 2 µM A23187. When monitoring LTB<sub>4</sub> production as a measure of cPLA<sub>2</sub> inhibition, the reaction was quenched with an equal volume of ice cold phosphate buffered saline. Cells were removed by centrifugation, and the LTB<sub>4</sub> present in the cell supernatant was measured  
20 using the LTB<sub>4</sub> scintillation proximity assay provided by Amersham according to the manufacturers directions. In the assays reported in the Tables above, LTB<sub>4</sub> was measured. When monitoring arachidonic acid production, the reaction was quenched with methanol containing D8-

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arachidonic acid as an internal reference. The lipids were extracted by the method of Bligh et al. ((1959) Can. J. Biochem. Physiol., 37, 911-917), and the fatty acid was converted to the pentafluorobenzyl ester and analyzed by GC-MS in a manner similar to that reported by Ramesha and Taylor ((1991) *Anal. Biochem.* 192, 173-180).

## References

- Altschul, S. F., Madden, T. L., Schäffer, A. A., Zhang, J., Zhang, Z., Miller, W., and Lipman, D. J. (1997). Gapped BLAST and PSI-BLAST: a new generation of protein database search programs. *Nucleic Acids Res.* *25*, 3389-3402.
- Bacon, D. J., and Anderson, W. F. (1988). A fast algorithm for rendering space-filling molecule pictures. *J. Mol. Graph.* *6*, 219-220.
- Balboa, M. A., Balsinde, J., Jones, S. S., and Dennis, E. A. (1997). Identity between the  $\text{Ca}^{2+}$ -independent phospholipase  $\text{A}_2$  enzymes from P388D<sub>1</sub> macrophages and chinese hamster ovary cells. *J. Biol. Chem.* *272*, 8576-8580.
- Bonventre, J. V., Huang, Z., Reza Taheri, M., O'Leary, E., Li, E., Moskowitz, M. A., and Sapirstein, A. (1997) Reduced fertility and postischemic brain injury in mice deficient in cytosolic phospholipase  $\text{A}_2$ . *Nature* *390*, 622-625.
- Börsch-Haubold, A. G., Bartoli, F., Asselin, J., Dudler, T., Kramer, R. M., Apitz-Castro, R., Watson, S. P., and Gelb, M. H. (1998). Identification of the phosphorylation sites of cytosolic phospholipase  $\text{A}_2$  in agonist-stimulated human platelets and HeLa cells. *J. Biol. Chem.* *273*, 4449-4458.
- Bricogne, G. (1993). Direct phase determination by entropy maximization and likelihood ranking: status report and perspectives. *Acta Cryst.* *D49*, 37-60.

Brünger, A. T., Krukowski, A., and Erickson J. (1990) Slow-cooling protocols for crystallographic refinement by simulated annealing. *Acta Cryst.* *A46*, 585-593.

Brünger, A.T. (1992a). The free R value: a novel statistical quantity for assessing the accuracy of crystal structures. *Nature* *355*, 472-474.

Brünger, A.T. (1992b). X-PLOR Version 3.1. A system for x-ray crystallography and NMR (New Haven: Yale University Press).

Clark, J. D., Lin, L.-L., Kriz, R. W., Ramesha, C. S., Sultzman, L. A., Lin, A. Y., Milona, N., and Knopf, J. L. (1991). A novel arachidonic acid-selective cytosolic PLA<sub>2</sub> contains a Ca<sup>2+</sup>-dependent translocation domain with homology to PKC and GAP. *Cell* *65*, 1043-1051.

Clark, J. D., Schievella, A. R., Nalefski, E. A., and Lin, L.- L. (1995). Cytosolic phospholipase A<sub>2</sub>. *J. Lipid Mediators Cell Signalling* *12*, 83-117.

Cleland, W. W., and Kreevoy, M. M. (1994). Low-barrier hydrogen bonds and enzymic catalysis. *Science* *264*, 1887-1890.

Collaborative Computing Project Number 4 (1994). *Acta Crystallogr.* *S760-763*.

Cowtan, K. D. and Main, P. (1996). Phase combination and cross validation in iterated density modification calculations. *Acta Crystallogr. D* *42*, 43-48.

Cygler, M. and Schrag, J. D. (1997). Structure as basis for understanding interfacial properties of lipases. *Meth. Enzymol.* *284*, 3-27.

Dennis, E. A. (1997). The growing phospholipase A<sub>2</sub> superfamily of signal transduction enzymes. *Trends Biochem. Sci.* **22**, 1-2.

De Carvalho, M. G. S., McCormack, A. L., Olson, E., Ghomaschi, F., Gelb, M., Yates III, J. R., and Leslie, C. C. (1996). Identification of phosphorylation sites of human 85kda cytosolic phospholipase A<sub>2</sub> expressed in insect cells and present in human monocytes. *J. Biol. Chem.* **271**, 1-11.

De La Fortelle, E., and Bricogne, G. (1997). Maximum-likelihood heavy-atom parameter refinement for multiple isomorphous replacement and multiwavelength anomalous diffraction methods. *Methods Enzymol.* **276**, 494-523.

Derewenda, Z. S., and Derewenda, U. (1991). Relationships among serine hydrolases: evidence for a common structural motif in triacylglyceride lipases and esterases. *Biochem. Cell. Biol.* **69**, 842-851.

Duggleby, H. J., Tolley, S. P., Hill, C. P., Dodson, E. J., Dodson, G., and Moody, P. C. E. (1995). Penicillin acylase has a single-amino-acid catalytic centre. *Nature* **373**, 264-268.

Essen, L.-O., Perisic, O., Cheung, R., Katan, M., & Williams, R. L. (1996). Crystal structure of a mammalian phosphoinositide-specific phospholipase C $\beta$ . *Nature* **380**, 595-602.

Glover, S., de Carvalho, M., Bayburt, T., Jonas, M., Chi, E., Leslie, E., and Gelb, M. (1995) Translocation of the 85-kDa phospholipase A<sub>2</sub> from cytosol to the nuclear envelope in rat basophilic leukemia cells stimulated with calcium ionophore or IgE/antigen. *J. Biol. Chem.* **270**, 15359-15367.



Grobler, J. A., Essen, L.-O., Williams, R. L., and Hurley, J. H. (1996). C2 domain conformational changes in phospholipase C $\alpha$ . *Nat. Struct. Biol.* **3**, 788-795.

Hanel, A. M., and Gelb, M. H. (1993). Processive interfacial catalysis by mammalian 85-kilodalton phospholipase A<sub>2</sub> enzymes on product-containing vesicles: application to the determination of substrate preferences. *Biochemistry* **32**, 5949-5958.

Hanel, A. M., and Gelb, M. H. (1995). Multiple enzymatic activities of the human cytosolic 85-kDa phospholipase A<sub>2</sub>: hydrolytic reactions and acyl transfer to glycerol. *Biochemistry* **34**, 7807-7818.

Hattori, M., Adachi, H., Tsujimoto, M., Arai, H., and Inoue, K. (1994). The catalytic subunit of bovine brain platelet-activating factor acetylhydrolase is a novel type of serine esterase. *J. Biol. Chem.* **269**, 23150-23155.

Hattori, M., Adachi, H., Aoki, J., Tsujimoto, M., Arai, H., and Inoue, K. (1995). Cloning and expression of a cDNA encoding the beta-subunit (30-kDa subunit) of bovine brain platelet-activating factor acetylhydrolase. *J. Biol. Chem.* **270**, 31345-31352.

Hendrickson, W. A. (1991). Determination of macromolecular structures from anomalous diffraction of synchrotron radiation. *Science* **254**, 51-58.

Hixon, M. S., Ball, A., and Gelb, M. H. (1998). Calcium-dependent and -independent interfacial binding and catalysis of cytosolic group IV phospholipase A<sub>2</sub>. *Biochemistry* **37**, 8516-8526.

Huang, Z., Payette, P., Abdullah, K., Cromlish, W. A., and Kennedy, B. P. (1996). Functional identification of the active-site nucleophile of the human 85-kDa cytosolic phospholipase A<sub>2</sub>. *Biochemistry* *35*, 3712-3721.

Kramer, R. M., Roberts, E. F., Manetta, J., and Putnam, J. E. (1991). The Ca<sup>2+</sup>-sensitive cytosolic phospholipase A<sub>2</sub> is a 100-kDA protein in human monoblast U937 cells. *J. Biol. Chem.* *266*, 5268-5272.

Kraulis, P. J. (1991). MOLSCRIPT: a program to produce both detailed and schematic plots of protein structures. *J. Appl. Cryst.* *24*, 946-950.

Leslie, C. C. and Channon, J. Y. (1990). Anionic phospholipids stimulate an arachidonoyl-hydrolyzing phospholipase A<sub>2</sub> from macrophages and reduce the calcium requirement for activity. *Biochim. Biophys. Acta* *1045*, 261-270.

Leslie, C. C. (1997). Properties and regulation of cytosolic phospholipase A<sub>2</sub>. *J. Biol. Chem.* *272*, 16709-16712.

Lin, L.-L., Lin, A. Y., and DeWitt, D. L. (1992a) IL-1  $\beta$  induces the accumulation of cPLA<sub>2</sub> and the release of PGE<sub>2</sub> in human fibroblasts. *J. Biol. Chem.* *267*, 23451-23454.

Lin, L.-L., Lin, A. Y., and Knopf, J. L. (1992b) Cytosolic phospholipase A<sub>2</sub> is coupled to hormonally regulated release of arachidonic acid. *Proc. Natl. Acad. Sci. USA* *89*, 6147-6151.

Lin, L.-L., Wartmann, M., Lin, A. Y., Knopf, J. L., Seth, A., and Davis, R. J. (1993) cPLA<sub>2</sub> is phosphorylated and activated by MAP kinase. *Cell* *72*, 269-278.

Matagne, A., Lamotte-Brasseur, J., and Frère, J.-M. (1998). Catalytic properties of class A  $\beta$ -lactamases: efficiency and diversity. *Biochem. J.* **330**, 581-598.

Mosior, M., Six, D. A., and Dennis, E. A. (1998). Group IV cytosolic phospholipase A<sub>2</sub> binds with high affinity and specificity to phosphatidylinositol 4,5-bisphosphate resulting in dramatic increases in activity. *J. Biol. Chem.* **273**, 2184-2191.

Murshudov, G. N., Vagin, A. A., and Dodson, E. J. (1997) *Acta Crystallogr. Sect. D.* **53**, 240-255.

Nalefski, E. A., Sultzman, L. A., Martin, D. M., Kriz, R. W., Towler, P. S., Knopf, J. L., and Clark, J. D. (1994) Delineation of two functionally distinct domains of cytosolic phospholipase A<sub>2</sub>, a regulatory Ca<sup>2+</sup>-dependent lipid-binding domain and a Ca<sup>2+</sup>-independent catalytic domain. *J. Biol. Chem.* **269**, 18239-18249.

Nalefski, E. A., and Falke, J. J. (1996). The C2 domain calcium-binding motif: structural and functional diversity. *Protein Sci.* **12**, 2375-2390.

Nalefski, E. A., McDonagh, T., Somers, W. , Seehra, J., Falke, J. J., and Clark, J. D. (1998). Independent folding and ligand specificity of the C2 calcium-dependent lipid binding domain of cytosolic phospholipase A<sub>2</sub>. *J. Biol. Chem.* **273**, 1365-1372.

Nalefski, E. A., and Falke, J. J. (1998). Location of the membrane-docking face on the Ca<sup>2+</sup>-activated C2 domain of cytosolic phospholipase A<sub>2</sub>. *Biochemistry* **37**, 17642-17650.

Nicholls, A. (1992). GRASP: Graphical representation and analysis of surface properties (Columbia University, New York).

O'Byrne, P. M. (1997) Leukotrienes in the pathogenesis of asthma. *Chest* *111*, 27S-34S.

Otwinowski, Z. (1993). In Data Collection and Processing. L. Sawyer, N. Isaacs, and S. W. Bailey, eds. (Daresbury, U. K.: Science and Engineering Council), pp. 56-62.

Perisic, O., Fong, S., Lynch, D. E., Bycroft, M., & Williams, R. L. (1998). Crystal structure of a calcium-phospholipid binding domain from cytosolic phospholipase A<sub>2</sub>. *J. Biol. Chem.* *273*, 1596-1604.

Pickard, R. T., Chiou, X. G., Striffler, B. A., DeFelippis, M. R., Hyslop, P. A., Tebbe, A. L., Yee, Y., K., Reynolds, L. J., Dennis, E. A., Kramer, R. M., & Sharp, J. D. (1996). Identification of essential residues for the catalytic function of 85-dKa cytosolic phospholipase A<sub>2</sub>. *J. Biol. Chem.* *271*, 19225-19231.

Qiu, Z.-H., Gijón, M. A., de Carvalho, M. S., Spencer, D. M., and Leslie, C. C. (1998). The role of calcium and phosphorylation of cytosolic phospholipase A<sub>2</sub> in regulating arachidonic acid release in macrophages. *J. Biol. Chem.* *273*, 8203-8211.

Rao, V. D., Misra, S., Boronekov, I. V., Anderson, R. A., and Hurley, J. H. (1998). Structure of type IIbeta phosphatidylinositol phosphate kinase: a protein kinase fold flattened for interfacial phosphorylation. *Cell* *94*, 829-839.

- Reynolds, L. J., Hughes, L. L., Louis, A. I., Kramer, R. M., and Dennis, E. A. (1993). Metal ion and salt effects on the phospholipase A<sub>2</sub>, lysophospholipase, and transacylase activities of human cytosolic phospholipase A<sub>2</sub>. *Biochim. Biophys. Acta* 1167, 272-280.
- Schievella, A. R., Regier, M. K., Smith, W. L., and Lin, L.-L. (1995). Calcium-mediated translocation of cytosolic phospholipase A<sub>2</sub> to the nuclear envelope and endoplasmic reticulum. *J. Biol. Chem.* 270, 30749-30754.
- Schrag, J. D. and Cyger, M. (1997). Lipases and  $\alpha/\beta$  hydrolase fold. *Meth. Enzymol.* 284, 85-107.
- Scott, D. L., White, S. P., Zbyszcz, O., Yan, W., Gelb, M. H., and Sigler, P. B. (1990). Interfacial catalysis: the mechanism of phospholipase A<sub>2</sub>. *Science* 250, 1541-1546.
- Sharp, J. D., White, D. L., Chiou, X. G., Goodson, T., Gamboa, G. C., McClure, D., Burgett, S., Hoskins, J., Skatrud, P. L., Sportsman, J. R., Becker, G. W., Kang, L. H., Roberts, E. F., and Kramer, R. M. (1991). Molecular cloning and expression of human Ca<sup>2+</sup>-sensitive cytosolic phospholipase A<sub>2</sub>. *J. Biol. Chem.* 266, 14850-14853.
- Sharp, J. D., Pickard, R. T., Chiou, X. G., Manetta, J. V., Kovacevic, S., Miller, J. R., Varshavsky, A. D., Roberts, E. F., Striffler, B. A., Brems, D. N. et al. (1994). Serine 228 is essential for catalytic activities of 85-kDa cytosolic phospholipase A<sub>2</sub>. *J. Biol. Chem.* 269, 23250-23254.
- Simon, L. S., Lanza, F. L., Lipsky, P. E., Hubbard, R. C., Talwalker, S., Schwartz, B. D., Isakson, P. C., and Geis, G. S. (1998). Preliminary study of

the safety and efficacy of SC-58635, a novel cyclooxygenase 2 inhibitor: efficacy and safety in two placebo-controlled trials in osteoarthritis and rheumatoid arthritis, and studies of gastrointestinal and platelet effects. *Arthritis Rheum.* *41*, 1591-1602.

Tang, J., Kriz, R. W., Wolfman, N., Shaffer, M., Seehra, J., and Jones, S. S. (1997). A novel cytosolic calcium-independent phospholipase A<sub>2</sub> contains eight ankyrin motifs. *J. Biol. Chem.* *272*, 8567-8575.

Tjoelker, L. W., Wilder, C., Eberhardt, C., Stafforini, D. M., Dietsch, G., Schimpf, B., Hooper, S., Le Trong, H., Cousens, L. S., Zimmerman, G. A., et al. (1995). Anti-inflammatory properties of a platelet-activating factor acetylhydrolase. *Nature* *374*, 549-553.

Trimble, L. A., Street, I. P., Perrier, H., Tremblay, N. M., Weech, P. K., and Bernstein, M. A. (1993). NMR structural studies of the tight complex between a trifluoromethyl ketone inhibitor and the 85-kDa human phospholipase A<sub>2</sub>. *Biochemistry* *32*, 12560-12565.

Underwood, K. W., Song, C., Kriz, R. W., Chang, X. J., Knopf, J. L. & Lin, L.-L. (1998). A novel calcium-independent phospholipase A<sub>2</sub>, cPLA2- $\beta$ , that is prenylated and contains homology to cPLA2. *J. Biol. Chem.* *273*, 21926-21932.

Uozumi, N., Kume, K., Nagase, T., Nakatani, N., Ishii, S., Tashiro, F., Komagata, Y., Maki, K., Ikuta, K., Ouchi, Y., Miyazaki, J.-i., & Shimizu, T. (1997). Role of cytosolic phospholipase A<sub>2</sub> in allergic response and parturition. *Nature* *390*, 618-622.

Venable, M. E., Olson, S. C., Nieto, M. L., and Wykle, R.L. (1993). Enzymatic studies of lyso platelet-activating factor acylation in human neutrophils and changes upon stimulation. *J. Biol Chem* 268, 7965-7975.

Xu, G.-Y., McDonagh, T., Yu, H.-A., Nalefski, E., Clark, J. D., & Cumming, D. A. (1998). Solution structure and membrane interactions of the C2 domain of cytosolic phospholipase A<sub>2</sub>. *J. Mol. Biol.* 280, 485-500.

All references cited herein are incorporated herein by reference as if fully set forth.